Tide changes expose shells on the beach at Potlach State Park on Hood Canal. *Rae A. McNally*

UNCERTAIN FUTURE

Changes in the Waters of Puget Sound

Puget Sound supports a stunning diversity of life within and around its waters. Fluctuations in climate and sea level play a role in determining the suitability of these habitats through their influence on circulation and water properties.

Sea level rise

Sea level naturally rises and falls over the course of hours, months and years. Sea level fluctuates most in the twice-daily tides. Variations in atmospheric pressure and wind patterns produce sea level changes (up or down) on timescales of days to decades. Local land movements affect local sea level on timescales of centuries or suddenly during earthquakes.

In addition, global sea level has been increasing at an estimated rate of 4-8 inches over the 20th century (1.0 to 2.0 mm/yr) as a result of both the warming of ocean waters, which causes thermal expansion, and the melting of glaciers, small ice fields and polar ice sheets.[25]

Complex geological factors produce different rates of sea level rise across the Puget Sound region.[26] Land is sinking in much of Puget Sound, with rates ranging from zero in the eastern Strait of Juan de Fuca and north Puget Sound to more than 8 inches per century (2 mm/yr) in south Puget Sound.[27] Thus, net local sea level rise in north Puget Sound is close to the global average, and is up to double the global average in south Puget Sound.

Future global sea level rise is likely to accelerate as a result of human-caused global warming, with changes likely in the range of 4-35 inches (0.09-0.88 m) during the 21st century. This is one of the best understood and predictable components of future climate change.[28] Some climate models suggest additional sea level rise in coastal waters—which would affect Puget Sound—associated with changes in winds, on the order of an additional 8 inches (20 cm).[29] Adding these changes to the geological changes, it appears likely that sea level rise in Puget Sound will proceed at least as rapidly as, if not faster than, the global average rate of increase with rates varying around the Sound, depending on land uplift or sinkage (Figure 6).

Circulation in Puget Sound

The circulation of Puget Sound—the meeting and mixing of saltwater from the Pacific Ocean and freshwater from the region's many rivers—is strongly influenced by the Sound's salinity, temperature and geography.

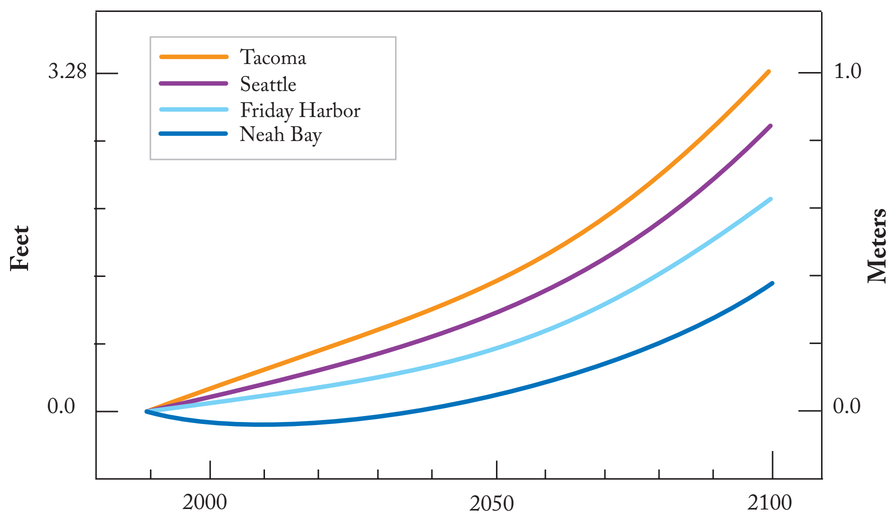
The Sound is a glacially carved basin separated from the Strait of Juan de Fuca by a shallow (144 feet, or 44m) sill at the north end of Admiralty Inlet that limits the exchange of water between the Sound and the Strait. The Sound's circulation is dominated by:

- The addition of freshwater at the surface, which generally flows seaward and must be balanced by inflow of salty water at depth,
- Tidal stirring, especially at the sill at Admiralty Inlet. Tidal stirring can be a significant force, pushing as much as 60 percent of the surface waters to great depth in the main basin.[30]

The Whidbey sub-basin receives freshwater from the Skagit River, the largest in the Sound, and usually has sharply stratified or layered waters with a shallow (about 30 feet, or about 10 m), surface layer of relatively fresh water. The numerous inlets of the south Sound often have warm surface water in summer. Hood Canal has a shallow sill of 160 feet (50 m) at the mouth and is also long, deep and narrow, resulting in the slowest circulation of the sub-basins. This slow exchange causes the southern end to become especially susceptible to periods of hypoxic or oxygen-deprived conditions at depth.

> *"Global sea level has been increasing at an estimated rate of 4–8 inches over the 20th century."*

Changes in timing of freshwater input may affect the circulation, stratification and mixing of the Sound, but the subject is largely unstudied. The higher freshwater inputs during certain climatic periods (such as the cool phase PDO, 1947-1976) cause the inflow of salty water to be shallower than under drier conditions when the inflow is nearer the bottom.[31] The decrease in freshwater inflow to the Puget Sound-Georgia Basin during the drought of 2000-2001 resulted in a four-fold reduction in the outflow of surface water through the Strait of Juan de Fuca.[32]



Sea Level Rise Scenarios

Figure 6: Future sea level rise scenarios for various locations in Puget Sound. These sea level rise curves account for projected global sea level rise, the increased rate projected for the NE Pacific and the sinking of local land. The degree of sea level rise projected at Tacoma for 2050 (about 1.3 feet or 0.4 m) would not occur at Seattle until around 2060 and at Friday Harbor until around 2080. Depending on the various climate sensitivity factors and response option assumptions, the sea level rise scenarios could be 20 percent to nearly 200 percent of the mid-range scenario depicted.[82]

Detailed studies using model simulations are needed and should include human-influenced changes such as land use and water management. Some of the tools needed for a more detailed assessment have already been assembled as part of the Puget Sound Regional Synthesis Model (PRISM) research effort at the University of Washington.[33]

Washington state coastal beaches.

Coastal upwelling

The characteristics of saltwater coming into Puget Sound are determined in large part by climate conditions along Washington's ocean coast.

Summertime winds from the north drive coastal upwelling along the Pacific coast, bringing cold, salty and nutrient-rich deep water to the surface. Periods of weak or southerly winds following upwelling events frequently sweep the upwelled waters along the coast into the Strait of Juan de Fuca. The strength and timing of coastal upwelling varies considerably from weeks to decades. How the upwelling of biologically important nutrients changes as a result of global warming will be influenced by future changes in large-scale atmospheric circulation and local winds, although current climate model simulations suggest that crucial wind patterns are relatively insensitive to global warming.[34]

> *"Of the water quality problems identified in the Puget Sound basin in 2004, 20 percent were related to river temperatures that exceeded critical threshold values."*

Further studies of upwelling are needed to more accurately predict changes in upwelled nutrients.

Water quality

Key properties that characterize the physical and biological function of fresh and marine waters in Puget Sound include water temperature, salinity, density, stratification (layering), dissolved oxygen, nutrients and fecal coliform levels. These water properties are influenced by fluctuations in Pacific Ocean water, freshwater inputs, and local weather conditions. While human influences are often the primary cause of water quality degradation, climate variability and change may worsen water quality problems when these changes exceed the buffering capacity of the system.[35]

Water temperature

Water temperature is an important factor controlling the suitability of habitats for freshwater and marine organisms and physical, biological and chemical processes important in the food web. Many Puget Sound species, such as salmon, oysters and groundfish, depend on cold water. Of the water quality problems identified in the Puget Sound basin in 2004, 20 percent were related to river temperatures that exceeded critical threshold values.[36]

Many factors contribute to increased water temperature in freshwater and marine systems. Climate plays a role in determining water temperature via its influence on air temperature, the temperature of stream and river inflows, and the degree of stratification in marine systems.

Information on trends in water temperature for freshwater and marine water systems in the Puget Sound basin is limited, but there is evidence of warming during the 20th century. Long-term records show Lake Washington warming substantially since the 1960s.[37]

There are no long-term measurements of sea surface temperature in Puget Sound itself, but there are nearby records that indicate warming over the 20th century. Measurements at the Race Rocks lighthouse in the Strait of Juan de Fuca near Victoria, BC date back to 1921 and indicate decadal-scale fluctuations and a long-term warming trend of 1.7˚F (0.9˚C) since 1921 and 1.8˚F (1.0˚C) since 1950 (Figure 7). Research using the internal growth rings of geoduck shells as an indirect record of sea surface temperature in the Strait of Juan de Fuca found the 1990s to be the warmest decade in a record dating to the 1840s for March through October sea surface temperatures in the Strait of Juan de Fuca.[38] Sea surface temperature variations studied over shorter time periods during the late 1990s show a correlation with air temperatures.[39]

Looking toward the future, global warming is almost certain to lead to additional warming of the surface waters of Puget Sound and its tributary rivers as a result of the projected increases in regional temperature and decreases in summer stream flow.

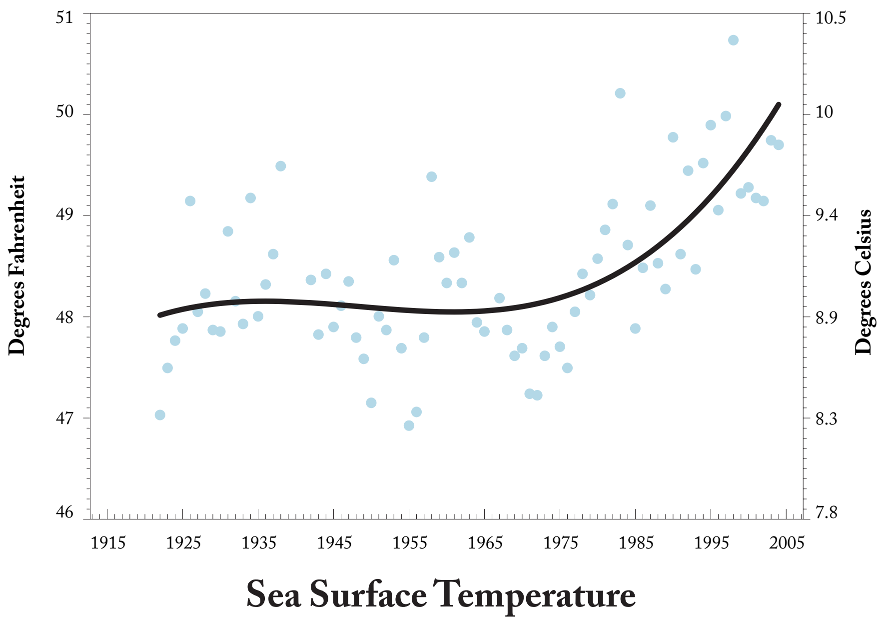


Figure 7: Average annual sea surface temperature at Race Rocks, near Victoria, BC. Each year's temperature is shown as a circle and the smooth curve indicates a long-term warming trend of 1.7°F (0.9°C) since 1921 and 1.8°F (1°C) since 1950.

Salinity

Sea surface salinity or saltiness is an important determinant of water density, which in turn influences circulation patterns and marine habitat conditions. Major influences on sea surface salinity in Puget Sound marine waters are: the salinity content of Pacific Ocean water entering through the Strait of Juan de Fuca, and the amount and timing of freshwater inflows from Puget Sound basin rivers and streams.

Unfortunately, no long-term records of salinity exist for Puget Sound and trends related to climate cannot be calculated, but measurements taken in the 1990s indicate that years with lower stream flows have coincided with higher sea surface salinity and high stream flow with low salinity, as expected.[40] Records at Race Rocks since 1936 show that fluctuations in salinity are correlated with Puget Sound-area winter precipitation. Salinity has slightly decreased during this time, although this salinity trend cannot be explained by the trend in precipitation.

It is likely, then, that the observed changes in stream flows noted previously have increased salinity in summer and decreased it in winter, and projected future changes in freshwater inputs would cause larger changes of salinity.

Stratification

A stratified or layered water column has properties (density, nutrient content, etc.) that change rapidly with depth. Stratification occurs in waters where mixing, such as by winds and tides, is low. The degree of stratification affects upwelling of nutrient supplies to surface waters, phytoplankton growth, the availability of dissolved oxygen to waters at depth, and pollutant flushing.[41]

Stratification in marine waters is largely driven by water temperature and salinity. Cold and/or salty water is denser and tends to sink, while warmer and/or fresher water lies above the colder layer. As a result, freshwater is more difficult to mix down into the water column and water rich in dissolved oxygen remains confined to the surface.

In many areas of Puget Sound, variations in salinity resulting from freshwater input from nearby rivers are the main control on stratification.[42] Increasing solar radiation, weak winds, and weak water circulation also increase stratification.[43] The reduced freshwater inflow during the 2000-2001 drought resulted in a 56 percent average reduction in stratification in greater Puget Sound.[44]

In winter months, projected increases in stream flow would increase stratification in Puget Sound. In summer months the expected change is less clear—there will be some cancellation between increased surface water temperature (which would increase stratification) and the increased surface salinity resulting from reduced stream flow (which would decrease stratification). Which one of these processes dominates will likely vary regionally in the Sound depending on circulation processes in different locations.

> *"It seems probable that dissolved oxygen levels at depth could decrease, increasing hypoxic conditions in bottom water."*

Dissolved oxygen

The amount of dissolved or free[45] oxygen in water helps determine habitat suitability for fish and other organisms. Deep waters extremely low in dissolved oxygen can stress or even kill fish. The amount of dissolved oxygen (DO) can be reduced by a variety of factors, including:

- Higher water temperature,
- Stratification of the water column, which confines low-DO water at depth,
- Freshwater inflows with high organic content or low DO,
- Coastal upwelling of low-DO deep water at the entrance to the Strait of Juan de Fuca,
- Decomposition of organic material.[46]

Low DO is common in the sub-surface waters of Puget Sound (deeper than approximately 65 feet, or 20 m), with 56 percent of monitoring sites reporting DO below the threshold of 5 ppm (5 mg/L).[47] This threshold is considered to be a concentration that causes stress in biological organisms.

Studies have linked periods of low DO in the 1990s with reduced flushing of Puget Sound waters and reduced freshwater inflow. Trends in DO have not emerged since routine monitoring began only in 1993. Thus more studies are needed to more fully understand how projected climate change may affect DO levels in Puget Sound's waters.

Evaluating the factors controlling DO and the likely direction of change that each might experience in a warming climate, it seems probable that DO levels at depth could decrease, increasing hypoxic conditions in bottom water. This is because increased surface populations of marine plants and animals (resulting from higher water temperature and greater winter stratification) would result in increased consumption of oxygen at depth when they die and sink.

Modeling studies should be conducted to determine the relative importance of changing climate influences (for example changes in winds, cloudiness and freshwater inputs) versus changing nutrient inputs from septic tanks, fertilizer runoff and land use practices.

Nutrients

Nutrient inputs such as nitrogen and phosphorus have important effects on the biological and chemical processes necessary to support freshwater and marine species in Puget Sound. Too few nutrients can limit primary productivity while too many nutrients can lead to excess primary production and oxygen depletion via decomposition of the excess organic matter. Nutrient-rich inputs into Puget Sound include stormwater runoff, industrial waste discharges, failing septic systems, tributary inflows and coastal upwelling. Surface water nutrient levels are also influenced by stratification and organic productivity (decreasing with increased stratification or productivity).

Monitoring of nitrogen and phosphorus in freshwater rivers and lakes in the Puget Sound area began in 1991. Most of the 20 sites monitored had no significant trends during the 1990s, but three had declining trends in total nitrogen and five had increases in total phosphorus.[48] In the Sound, three locations —Budd Inlet, south Hood Canal and Penn Cove—have been identified as exceptionally sensitive to eutrophication,[49] which is a process where water bodies receive excess nutrients that stimulate excessive plant growth (algae and submerged aquatic vegetation). This enhanced plant growth, often called an algal bloom, reduces dissolved oxygen in the water when dead plant material decomposes, and can cause other organisms to die. Many more sites around the Sound also have been identified as sensitive to eutrophication.[50]

Regional climate change will affect surface mixed layer nutrient levels via changes in sea level (increased leakage from septic systems), biological productivity, and freshwater inflow. Future nutrient levels will also depend on changes in sources related to human activities, such as agricultural and home gardening practices.

The overall impact of climate change is hard to project because of incomplete knowledge of the relative importance of potentially competing influences. Freshwater inflow, for example, has the potential to both increase and decrease nutrient concentrations. Increased runoff, which could increase nutrient delivery, results in increased stratification of the Sound and therefore increased depletion of nutrients by phytoplankton. Really high runoff in some urban areas may overwhelm sewage treatment plants, leading to more frequent sewer system overflows and therefore increased nutrient concentrations. The overall change will hinge on the balance among these various effects.

Fecal coliform and other pollutants

Fecal coliform is used as an indicator of potentially harmful bacteria and viruses from human and animal wastes. Fecal coliform enters fresh and marine water bodies primarily through stormwater runoff, failing septic systems, combined sewer overflows, livestock operations, and

Livestock runoff can contaminate nearby waters. Pictured here, a Midwest farm.

contaminated freshwater inputs from rivers and streams. Fecal coliform is a major concern because it can contaminate beaches and shellfish harvesting in Puget Sound. Forty-one percent of water quality problems identified in the Puget Sound basin in 2004 were related to fecal coliform bacteria.[51]

Recent trends in fecal coliform levels in Puget Sound and nearby freshwater systems have been mixed, with some showing improvements and some showing deterioration over time. A climate connection has been suggested by the Washington Department of Ecology. During high precipitation periods between November 1998 and January 1999, and in November 1999, fecal coliform counts were particularly high \due most likely to increased runoff into nearshore waters.[52]

Future contamination by pollutants such as fecal coliform will be driven largely by future strategies for handling human and animal waste. Climate change could exacerbate problems with fecal coliform contamination because increased winter rains would likely lead to more stormwater runoff and combined sewer overflow events, as well as increased septic system leakage resulting from sea level rise.